Use of Amorphous and Microcrystalline Si Based Materials Grown at Rates of 10-15 Å/s as i-layers for Multi-Junction Solar Cells

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ABSTRACT

Using alternative techniques to the standard 13.56 MHz rf PECVD method, microcrystalline Si (μc-Si) and amorphous Si (a-Si) based devices have been fabricated at high i-layer growth rates (10-15 Å/s). Efficiencies of 9.6-10% have been achieved for devices with the μc-Si materials and stabilized efficiencies over 9% have been achieved for cells with a-Si(Ge) i-layers prepared at 10 Å/s.

1. Introduction

A microwave-based technique has been used to prepare μc-Si materials rates near 15 Å/s. Since the high deposition rates allow for fabrication of the required thicker μc-Si i-layers in a similar amount of time to that used for high quality a-SiGe i-layers (rates of 1-3 Å/s), the materials are attractive, low cost replacements for a-SiGe bottom cell i-layers in a-Si/a-SiGe and a-Si/a-SiGe/a-SiGe multi-junction cells whose fabrication requires expensive germane gas. Single-junction nip, a-Si/μc-Si and a-Si/a-SiGe/μc-Si devices have been fabricated in these studies.

Also in an effort to find an alternative deposition method to the standard low deposition rate 13.56 MHz PECVD technique, the feasibility of using a 70 MHz rf plasma frequency to prepare amorphous silicon (a-Si) based i-layer materials at high rates for nip based triple-junction solar cells has been tested. The use of high deposition rates will allow for higher machine throughputs in the solar module production lines. a-Si/a-SiGe/a-SiGe triple-junction solar cells have been fabricated with all of the i-layers prepared using the VHF technique and deposition rates near 10 Å/s. The results for both the μc-Si and a-Si studies are reported here.

2. Experimental

In both research programs, cells with total areas of 0.265 cm^2 and active areas of 0.25 cm^2 are being used to judge the material and device performance. Stainless steel substrates coated with current enhancing Ag/ZnO back reflectors are used as the substrates for preparation of the semiconductor structures. Both the thin doped layers and the thin a-Si:H buffer layers, grown between the VHF deposited a-SiGe:H i-layers and the doped layers, are prepared using the conventional 13.56 MHz PECVD process. To fabricate the a-Si:H and a-SiGe:H i-layers, a fixed VHF frequency of 70 MHz is used.

The μc-Si:H materials are prepared using a fixed 2.54 GHz microwave frequency. To fabricate nip solar cell structures, doped layers are prepared using the standard 13.56 MHz PECVD process and deposition rates near 1 Å/s. Also, current enhancing Ag/ZnO back reflectors are deposited on the stainless steel substrates prior to fabrication of the nip semiconductor structures.

For all cells after fabrication of the semiconductor structures, the devices are completed by depositing Indium Tin Oxide (ITO) conductive layers and then Aluminum (Al) collection grids. Both the ITO and Al layers are prepared using standard evaporation techniques.

3. Results

Microcrystalline Si

Under the standard AM1.5 white light conditions, stable efficiencies of 7.0% (Voc=0.543V, Jsc=21.2 mA/cm^2, FF=0.610) have been achieved for the μc-Si single-junction cells made using the i-layer growth rates of 15 Å/s [1-3]. These single-junction devices also exhibit a degradation of only 0-2% after long term (1000 hrs.) of light soaking demonstrating a high degree of stability. In Fig. 1, a spectral response curve for a μc-Si cell with the 7.0% efficiency is compared with the one for the PECVD a-SiGe cell (J_{sc}=26 mA/cm^2). Cells with higher J_{sc} (23 mA/cm^2) and higher microcrystalline fractions have been obtained, however they have lower efficiencies due to lower FF and V_{oc}. The lower FF and V_{oc} may be improved through further optimization of the doped layer conditions.

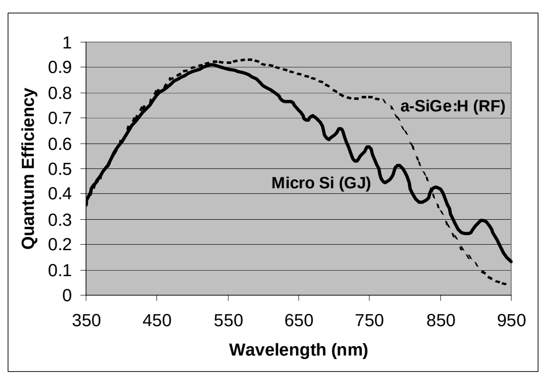

Fig. 1. Quantum Efficiency data for a-SiGe and μc-Si cells.

The high rate μc-Si cell has been used as a red-light absorbing component cell of a-Si/μc-Si and a-Si/a-SiGe/μc-Si structures. The a-Si and a-SiGe component cells of these structures were made at United Solar using i-layer growth rates near 1 Å/s. Fig. 2 displays an IV plot for the best a-Si/μc-Si cell made to date having an efficiency of 10.3%. A number of a-Si/μc-Si cell were light soaked for over 1000 hrs. under one sun conditions with the highest efficiencies listed in Table I. In the Table, the efficiencies are compared with those for a high quality a-S/a-Si device made at United Solar using an i-layer growth rate near 1 Å/s which was light soaked along with the a-Si/μc-Si cells. While the a-Si/a-Si devices have higher stable efficiencies, the difference is surprisingly small considering the rate at which the μc-Si cell was grown. Also, the percentage of degradation for the a-Si/μc-Si cells was significantly less. This could be due to the lower initial performance of the a-Si/μc-Si cells or the good stability of the μc-Si component cell. The a-Si/a-SiGe/μc-Si cells also display a low percentage of degradation after 1000 hrs. of light soaking (7% compared with 10-13% observed for high quality a-Si/a-Si/a-SiGe cells). Again, the initial efficiencies for the a-Si/a-SiGe/μc-Si cells (11.4%) are lower than for the a-Si/a-Si/a-SiGe cells (14.6%) [4]. Improvements to the efficiencies of the devices with the μc-Si component cells will likely come through improvements in the FF of the μc-Si cells and lower defect levels in the μc-Si materials.

A spectral response (QE) curve for a a-Si/μc-Si cell with the highest integrated total current (24 mA/cm^2) is shown in Fig. 3. While this device has a lower cell efficiency (10.1% initial), the QE data demonstrates that high currents are obtainable with the μc-Si component cells made at the 15 Å/s deposition rate.

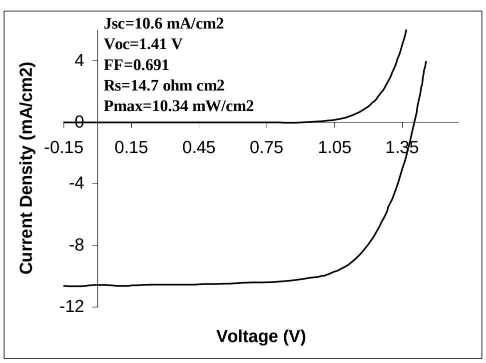

Fig. 2. IV data for a-Si/μc-Si cell prior to light soaking.

Table I.
IV data for a-Si/a-Si, a-Si/μc-Si and a-Si/a-SiGe/μc-Si cells (active area data)

Cell	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	P_{max} (mW/cm^2)	%. of Degr.
a-Si/μc-Si	1.44	10.2	0.656	9.57	6.4
a-Si/μc-Si	1.42	10.8	0.619	9.44	8.6
a-Si/a-Si	1.86	8.11	0.685	10.3	14.5
a-Si / a-SiGe/μc-Si	2.11	8.09	0.622	10.6	7.0

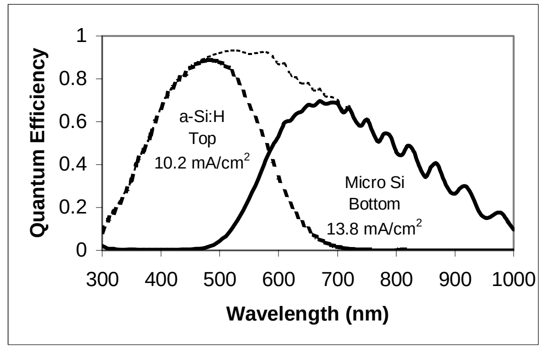

Fig. 3. Quantum efficiency data for a-Si/μc-Si cell.

High Rate a-Si/a-SiGe/a-SiGe

Representative IV data for a-Si/a-SiGe/a-SiGe cells made using the VHF technique and i-layer deposition rates near 10 Å/s are shown in Table II. Several cells with initial active area efficiencies near 11.2% and initial total area efficiencies of 10.4-10.6% have been fabricated. After 700 hrs. of light soaking, the total area cell efficiencies degrade to 9.3-9.4% with a percentage of degradation from the initial value of roughly 12%, a percentage typical of what is obtained for high efficiency triple-junction cells prepared using i-layer deposition rates near 1 Å/s. However, the stable efficiencies are presently lower than the 13% stable efficiencies obtained for cells made using the 1 Å/s rate[4].

The efficiencies for the triple-junction cells prepared at the high i-layer deposition rates are presently limited by the performance of the a-SiGe layers and cells [3,5]. A number of studies in which the ion bombardment conditions at the growing film surface were altered have been completed with no improvements noted. It is believed that a modification of the plasma chemistry during a-SiGe growth will be needed before high quality cells can be made at the 10 Å/s using the VHF technique. To that end, studies of the effect of deposition hardware on the growth chemistry and cell performance are now being carried out.

Table II. Total area properties for triple-junction cells.

Soak Time (hrs.)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	P_{max} (mW/cm^2)	%. of Degr.
0	2.35	6.56	0.687	10.6	-
700	2.31	6.17	0.658	9.38	11.5

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